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HANDS-FREE PRECISION CONTROL FOR EVA

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HANDS-FREE PRECISION CONTROL FOR EVA

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ABSTRACT

Extensive research into the use of the human foot-balancing reflex for control of vehicles in the one-g environment has led to an extrapolation of the concept to its use for Extra Vehicular Activity (EVA), the maneuvering of free-floating spacemen. An exploratory program in which zero-gravity was simulated for three degrees of freedom in the horizontal plane has proved the basic utility of the idea and provided a model for the preliminary design of a prototype, EVA control system.

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BACKGROUND

The use of the human balancing reflex for vehicular control was publicly propounded by Charles Zimmerman of the NACA in the early 1950's. His central thesis was that the learned pattern of reflexes used by a person in standing is essentially the same as that required to balance a force-vector supported platform, and hence should be directly applicable to the control of hovering type vehicles. This concept and its simple but dramatic demonstration by Zimmerman (Ref. 1) piqued the imagination of a great many aeronautical engineers and led shortly to several experiments with free-flying platforms of various sorts. There were, for example, the ducted-fan machine of Hiller (Ref. 2), the stand-on helicopter of DeLackner (the "Aerocycle" tested by Princeton University, Ref. 3), and several research-oriented devices built by the NACA (Refs. 4 and 5).

Since that initial period of activity, engineering interest has waned, probably for lack of definitive information on optimum usage of the human balancing reflex, and the concept has made only sporadic appearances in one or another embodiment; for example, the "lunar scooter" studied by North American, (Ref. 6) and the "Jet-Shoes" developed by NASA-Langley (Refs. 7 and 8). Grumman Research, however, has maintained a constant enthusiasm for the concept and has kept a small but steady effort going in the study of its application to various classes of vehicle and its significance to the fundamental understanding of human vehicular control behavior. This work, partially supported by the NASA, is described in Refs. 9 through 12.

A fairly extensive discussion of the advantages and potential applications of the balancing-reflex concept is given in Ref. 9. Of the items mentioned there, one of the most timely is the application to propulsion and control of the free-floating spaceman.

The difficulties encountered by a spaceman in attempting to do any significant amount of useful work outside his vehicle are by now well documented; they clearly stem from his inability to establish and maintain a required orientation of his body with respect to a "target" object without resorting to the use of clumsy restraining devices, dexterity prempting hand holds, and debilitating body contortions. Clearly, what the spaceman needs is a reasonably powerful and delicate means of controlling his body orientation that neither encumbers his hands nor requires him to fight his unyielding pressure suit. Adaptation of the natural, body-orienting responses of the feet and legs to the modulation of appropriately located thrusters appears to be a way to provide this means reliably, cheaply, and simply. The present document describes some preliminary work in this direction.

CHRONOLOGY OF THE DEVELOPMENT OF A SYSTEM

The development of a system for adapting natural, neuromuscular, body-orienting responses to the control of body-orienting thrusters for spacemen is, almost by definition, exploratory and experimental in nature. The particular problems and pitfalls likely to be encounttered cannot be predicted and so the work must proceed in a stepwise manner, each step directed by the experience obtained from the preceding ones. The following discussion is a chronology of the steps that have led, in the present case, to a workable EVA control configuration.

Simulators

Many ways of simulating zero-g have been used or suggested, but of course all have drawbacks of one kind or another. Water immersion, for example, produces large viscous forces and is not completely free of gravity effects, cable suspension becomes involved with complicated pendulum dynamics, and so forth.

For the resources at hand, the most practical compromise with reality appeared to be a three-degree-of-freedom simulation based on frictionless motion in the horizontal plane. The particular combination of degrees of freedom obtainable in a plane (two translations and one rotation) is reasonably defensible for exploratory work in zero-g simulation. It does provide a logical sort of consistency, a representation of the complete job of "getting around" in space (albeit two-space rather than three).

Of the three possible configurations for planar motion of the human body, the one involving pitch rotation (see Fig. 1) appeared to be the most appropriate for initial exploration. Thus the simulator or "scooter," as it came to be called, took the form of an articulated bed, carried by two levapad (air-bearing) supported tripods, upon which a person reclines. Although designed primarily to accommodate a man lying on his side as shown in Fig. 2, the device can be adapted readily to the supine position. The special floor on which the scooter glides is made of epoxy plastic poured over a concrete base, and is about 30 feet square, a more or less arbitrary compromise between desirability, availability, and expense.

Although the scooter could have been adapted to the standing position for examining yaw, it was not practical to do so. Therefore, a separate yaw simulator, a simple rotary device, was built for this purpose (see Fig. 3).

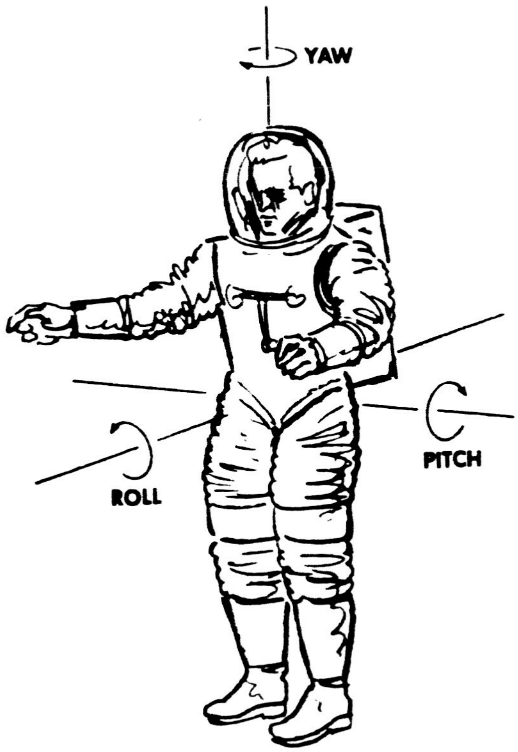


Fig. 1 The Rotational Axes

Fig. 2 The Basic Scooter

In all of the exploratory work carried out to date, the experimenters have served as the primary flyers and evaluators. Numerous others, including experienced pilots, however, have flown the simulators in various control configurations, and their impressions coincide generally with those expressed in the following sections. No astronauts have as yet participated.

The Original Control Configuration

The one-g, balancing-reflex concept, in its most elemental form, makes use of a single, supporting thruster which, with the aid of gravity, gives the flyer control of five degrees of freedom. It is the very essence of elegant simplicity. Thus it is not at all surprising that extrapolation of the idea to zero-g applications should center on basically the same configuration. This was in fact the case for the initial effort at Grumman, and the idea still prevails in the NASA Jet-Shoes work (Refs. 7 and 8).

Unfortunately, the very first simulator trials demonstrated quite clearly that the simple configuration could not provide what the Grumman research philosophy had established as a design goal: natural (unconscious), precise control of the body in space. An immediate and clear symptom of the problem was a complete absence of any feeling of "balancing," in the automatic sense which is typical of one-g jet-platform flying. Consequently there was no delicacy of control. The reasons for this (obvious in retrospect) also became quite clear. First, the

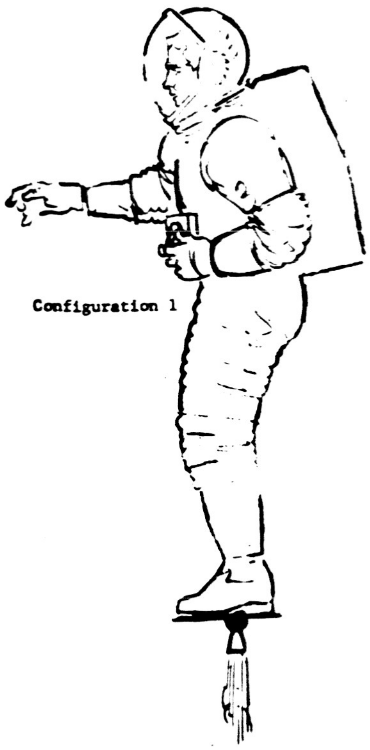


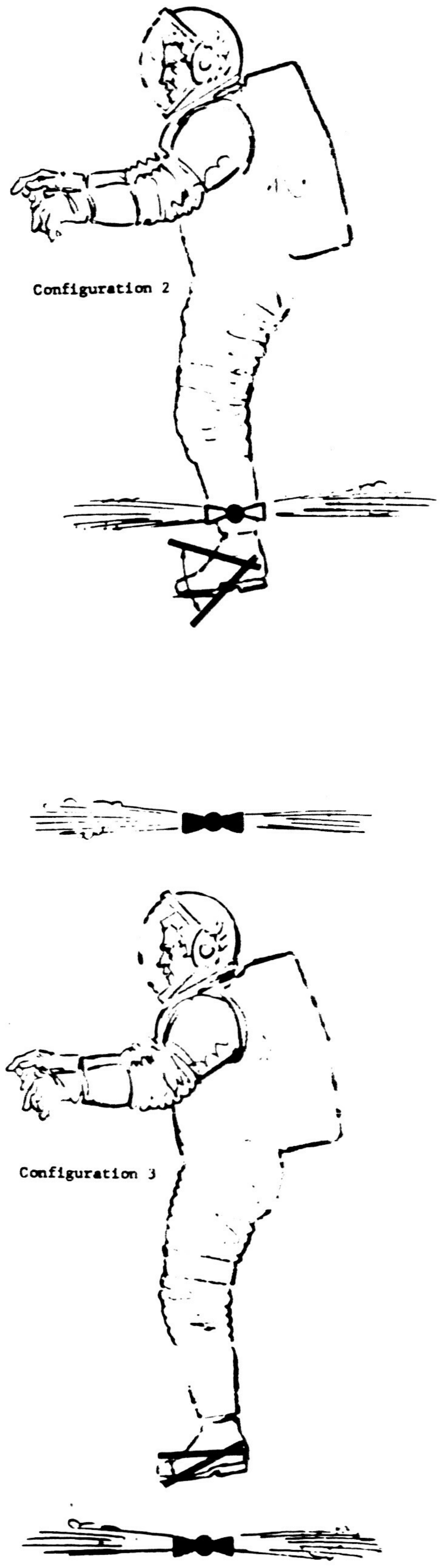
Fig. 3 Yaw Control Simulator

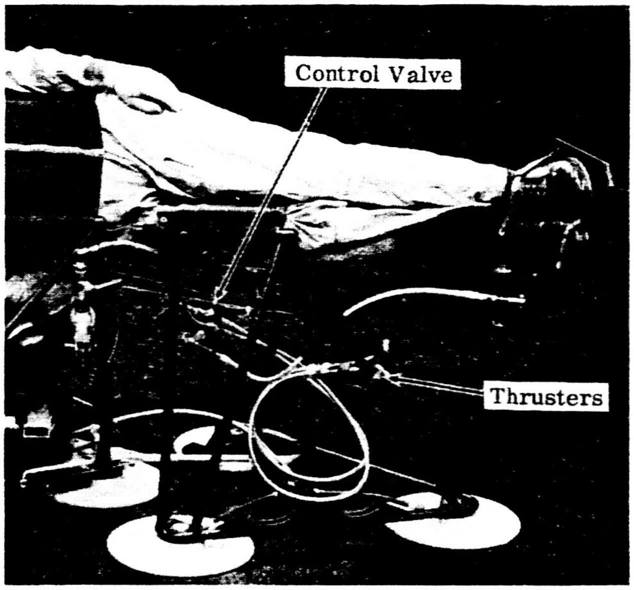
amount of thrust needed for fairly spirited maneuvers was very small (less than five pounds), hence the system gain, i.e., angular acceleration per degree of ankle deflection, was extremely low, orders of magnitude below the optimum for one-g balancing (as established by Ref. 9). Second, thrust was required only for brief periods, hence pitching responses did not inexorably follow ankle motions, as in the one-g jet platform, and there could be no sustained "feel" of the system.

Besides the basic balancing problem demonstrated by the brief series of experiments with the jet-platform configuration, a more subtle difficulty began to come to light. The original thinking had been that, in the absence of gravity (combining vectorially with thrust for forward motion; "walking" mode), translations would be accomplished primarily in a "swimming" mode (head or feet first), with up-and-down thrust controlled by knee flexing. It began to be apparent, however, that people have a natural inhibition against traveling any distance head-first or feet-first; a flyer insists that he must be able to look in the direction of motion, and if he cannot, as when he is inside a space suit, he becomes not only apprehensive, but faulty in his judgment of direction and speed. In light of the clear and inescapable conclusion regarding adherence to the Grumman objectives, some commentary on the apparent success of the Jet-Shoes concept (Refs. 7 and 8) is in order. As far as can be determined, the NASA personnel have adopted a quite different, but equally valid, set of ground rules. They, too, appear to have uncovered the same basic problem early in their experimentation, but they have chosen to sacrifice the high degree of control finesse inherent in natural balancing in favor of the extreme simplicity of Jet-Shoes. Their objective has become simply to provide the spaceman with a cheap and reasonably effective way of getting from one place to another, not to give him precision control when he gets there. As far as is known, they have not concerned themselves with the swimming-mode visual problem.

Control Configurations Two and Three

Following such abject but eye-opening failure of the simple concept to behave in zero-g even vaguely according to objectives, a certain amount of backtracking seemed to be necessary. The thinking had been along the lines that the simple jet, somewhat elaborated, might serve the complete control and propulsion function, as it does in one-g. It now appeared, however, that control of the various degrees of freedom would have to be separated and, perforce, evaluated one at a time. Pitch control, which is the most closely associated with balancing, seemed to be the appropriate function to look at first, and the scooter was therefore reworked to provide for a pair of crosswise (fore-and-aft) thrusters, located near the feet, and controlled, roughly proportionally, by a valve actuated mechanically by ankle deflection. Photographs of the configuration are shown in Fig. 4.





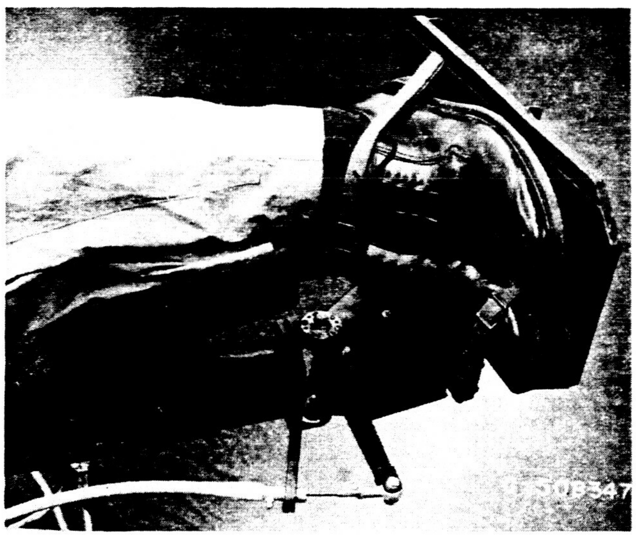


Fig. 4 Ankle Pivot and Thruster Arrangement for Configuration 2

The previous experiments had clearly brought out the need for higher system gain, but just how high it should be was moot. For one-g flight Ref. 9 had established an optimum gain in the vicinity of .1 g acceleration at the feet per degree of ankle deflection, but conceivably this value might not be in any way related to the requirement for zero-g flights. A simple side experiment using the research apparatus of Ref. 11, suitably modified (Fig. 5), indicated that the .1 g per degree value was probably valid. It turned out, however, that achievement of this value on the zero-g simulator, without the introduction of inordinate amounts of friction and backlash, was almost impossible. Therefore a compromise value of about .01 g per degree was set up. Results were encouraging; a feeling of balancing, though weak, was now clearly evident. But it was also evident that the gain was still far from satisfactory, and that there was a maneuvering problem in which the unbalanced forces produced by the thrusters during moderate rotational maneuvers built up a disconcerting spurious translation.

The lessons learned from the second configuration led to trial of Configuration 3 in which the single force was replaced by a couple, and the system gain was quadrupled by increasing the thruster moment arm and altering the control-valve linkage. The results of these changes, measured in terms of prior experience, were spectacular; pitch attitude control became entirely natural and effortless, permitting angular displacements to be made with precision, and "tumble" recoveries to be executed smartly. Roll control, briefly investigated with the flyer lying on his back, looked equally good. Friction and dead zone in the linkage, however, had been increased by the gain-changing alterations, and the dramatic elimination of other faults now caused these to stand out very clearly, especially dead zone, which had never really been encountered before in any of the one-g balancing experiments of Refs. 9 and 11.

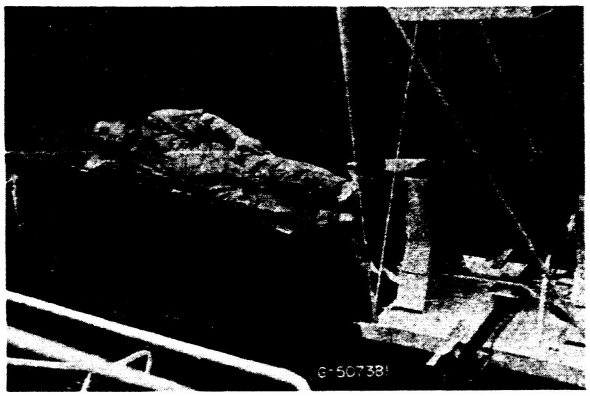


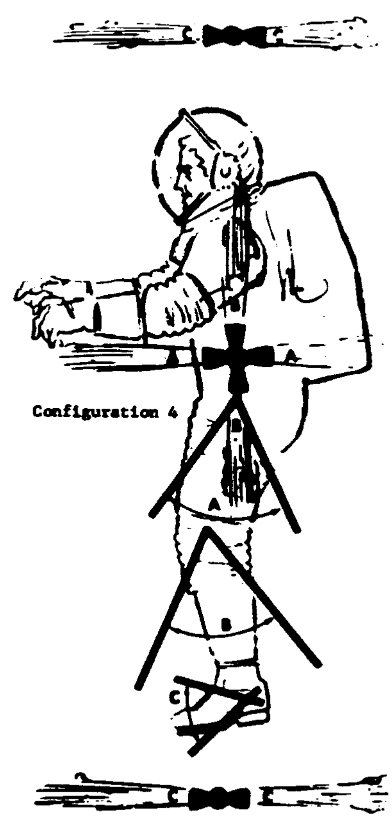
Fig. 5 One-g Simulator as Modified for "Zero-g" Trials

The Fourth Control Configuration

With the encouraging results achieved for pitch control alone, it seemed appropriate to turn attention to the two translational degrees of freedom: fore-and-aft and up-and-down.

There has been general agreement, dating back to the one-g jet platform work of Ref. 9, that "squatting" might be an appropriate mechanism for control of up-and-down thrust. Here, upward acceleration would be the natural and expected response to extension of the legs, and downward acceleration to retraction; the proper direction of response is clear and unambiguous. There is, however, a question about how the body deflection should be measured for transferral to a thruster control valve. The simplest arrangement seemed to be to pick up knee flexing at the appropriate joint in the simulator bed.

In an analogous fashion, waist-bending appeared to be an appropriate mechanism for the control of fore-and-aft thrust, but in this case the choice of direction of the response depends strongly on one's point of view. If one thinks in terms of leaning the upper body (buttocks fixed to the ground), then forward bending should produce forward motion. But if one adopts a "baby-walker" point of view in which the feet are fixed to the ground and the torso is propelled back and forth by the legs, then backward bending (backward thrust of the legs) should produce forward motion. The former arrangement seems to have a more elemental psychological appeal, and certain forms of human behavior can be pointed to in its support, e.g., the tendency of a highly involved observer of some action to "urge" an object toward a desired goal by leaning. The latter arrangement, on the other hand, is an exact analog of the clear-cut, vertical motion case, where the legs also propel the torso in the desired direction.



This philosophical controversy is perhaps resolved by considering that even in the baby-walker case the motion that initiates an action is a lean in the desired direction. It is this unconscious, precursor type of muscular response that would be expected to provide the most natural mechanism for control of the body. For Configuration 4, then, the body-lean philosophy was adopted. Waist flexure, measured between the thigh and torso, was picked up for transferral to the air valve mechanism by a lever extending between the upper and lower halves of the simulator bed. A system gain of about $1\frac{1}{2}$ pounds of thrust (or 1/300 g) per degree of body deflection was selected for both translational control modes on the basis of practical valve-linkage considerations.

Simultaneous operation of all three control modes became fairly successful after a little practice, but a single, glaring deficiency interfered with natural control. The manner of picking off waist bending required that thigh motion be reserved exclusively for fore-and-aft control, thereby precluding the use of true squatting for up-and-down control. Unfortunately, pure knee flexing turned out to be a highly unnatural substitute for squatting; unless the flyer put his mind to it, he invariably squatted for up-and-down commands, causing a most disconcerting, concomitant, fore-and-aft response. An occasional tendency to become confused in the use of the translational controls can probably be attributed to this cross-coupling effect, and it was interesting to note that dead zone (detrimental in the prior experiments) now seemed to be helpful for reorientation after a period of momentary confusion, raising the question of whether some sort of tangible neutrals might be desirable.

It was quite clear that pitch control remained good or perhaps even improved a bit when the flyer became preoccupied with his translational controls, which plainly demonstrated the value of "natural" neuromuscular mechanisms in this application.

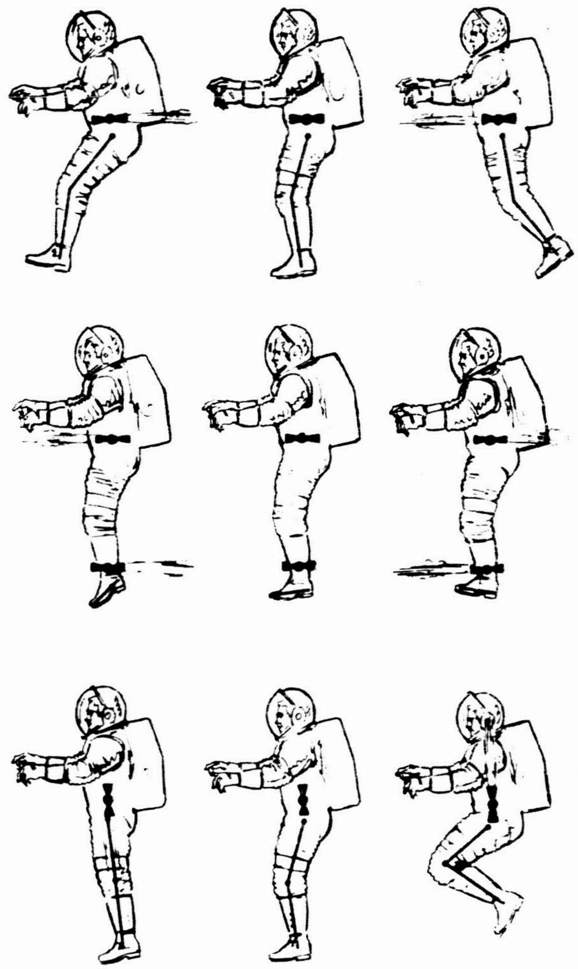
Although very little body motion could be seen, the translational control gains were judged to be far too low, even lower than the rotational gain, and there was a distinct feeling of disharmony between the modes.

Configuration Five: A Success

Configuration 5 might be considered a kind of culmination, because it represented for the first time, a truly workable system for spaceman maneuvering. On the simulator, the control valve linkage geometries had been modified to eliminate cross coupling between squatting and waist bending, and provision had been made for centering springs and detents on all three controls. Mechanical considerations did not permit any appreciable increase in the system gains over those used in Configuration 4, so the same questions concerning gain and gain harmony remained, but it turned out that the elimination of translational control cross coupling provided such a dramatic increment in naturalness that the gain problem lost much of its immediacy; the system, even with its low, inharmonious gains, became workable.

The scooter as shown in Fig. 6 was fairly extensively flown in simulated space task maneuvers, and a number of impressions about its flyability under various conditions emerged:

1) All three modes of control (ankle deflection, squatting, and waist bending) can be handled quite nicely, but with varying degrees of apparent naturalness. The relatively low gains of the translational modes almost certainly contribute to their lower quality, but there is a powerful experimental artifact that must raise serious doubt about any hasty judgment of control naturalness. This has to do with the <u>sound</u> of the control jets, which is loud, disconcerting, and often downright confusing. Because maneuvering is typically slow and deliberate, the motion cues (visual and proprioceptive) by which a flyer should operate, are weak and easily swamped by strong aural cues. Unfortunately there is a very strong urge, especially in the novice, to try to use the jet noise cues for flying. This <u>can</u>, in fact, be done for very simple maneuvers, but the sounds become hopelessly confusing in complex situations, and the flyer who has begun to rely on them often finds himself in a panic, unable (momentarily) to figure out what to do. It requires a strong effort of will for the novice to ignore the sound and attend only to the proper signals. Once he has learned to do this, however, his flying becomes much more instinctive.



Configuration 5

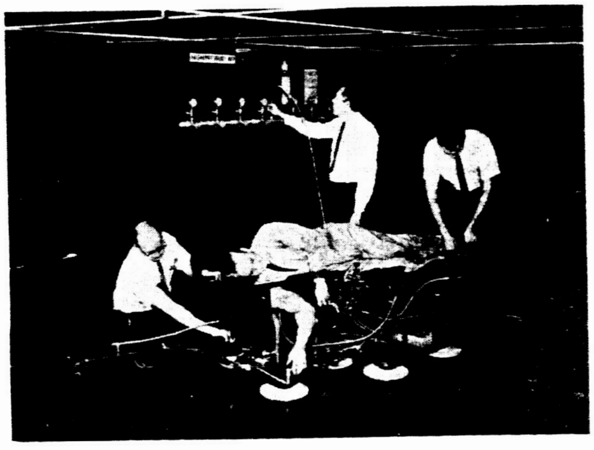


Fig. 6 The Scooter Arranged for Proportional Control

2) Centering springs on the controls are, in general, beneficial; they make it easier for the flyer, especially the novice, to find neutral. Detents, in the form of preloads on the springs, are also useful. A certain amount of care in the selection of spring rates and detent loads must be used, however, lest the flyer's natural coordination of hip and knee flexing in squatting be upset and, more critically, lest the subjective values of system gain be reduced.

It turns out, in this respect, that a flyer's interpretation of gain seems to be based on some over-all feeling of "effort" required to obtain a given response. Thus gain ought really to be expressed in terms of "acceleration per unit of effort," but it is not clear just how a flyer senses accelerations or how he defines "effort." Apparently, "effort" represents some combination of force and displacement, but just <u>what</u> combination is quite unknown. Its mathematical describing function undoubtedly is one in which the relative contributions of force and displacement to the subjective impression of gain change drastically with the spring rate, ranging from all-displacement at zero spring rate to all-force at infinite spring rate. A determination of this function for the various control modes could become the objective of some interesting additional experimentation.

Comparison of the flying characteristics of the scooter with and without centering springs is of some interest. It turns out that the novice is much more comfortable, and maneuvers more skillfully, with springs, but the experienced flyer apparently does equally well either way, and, in fact, if there is appreciable dead zone in the control system, may actually prefer no springs. Probably, as previously discussed, this is because the expert is able to ignore the sound of small residual jet flows resulting from his imprecision in neutralizing the valves. Such flows, though of negligible effect on maneuvering, are quite audible, hence difficult for the novice to ignore, and likely to cause him to go through a great deal of unnecessary struggle to eliminate them. Thus he prefers the springs, which permit him to shut off his jets completely simply by relaxing. The expert, on the other hand, tends to be annoyed by the springs because they demand more effort, particularly if there is a large dead zone to be pushed through before the jets come on. This line of thought now returns closely to the previous discussion about the meaning of "effort" in the operation of the control system. The expert's objection to the effort required to manipulate the springs appears to be based not so much on muscular "laziness" — forces (a pound or two) are, after all, far lower than people handle routinely without complaint — as on some sort of "control quickness" factor; in other words, "effort" seems to refer more to subtle difficulties with the response characteristics of the system (including the neuromuscular part). If this is in fact the case, the general study of gain previously suggested becomes all the more intriguing, and possibly quite important to the design of optimum systems.

3) Control power levels required for useful maneuvering are remarkably low. Maximum thrusts and torques typically used on the scooter (although more is available) are about 5 pounds and 15 foot-pounds, respectively which translate to about 2 pounds and 4 foot-pounds in the real spaceflight situation, where the thrusters do not have to move the considerable mass of the scooter. Such low values are certainly significant to the design of a practical system.

On-Off Control

There are two, potential, major advantages to the use of on-off operation in the present application: thruster control may be simpler, and fuel specific impulse may be greater. Thus the flying qualities of on-off control systems are of some importance to the over-all picture.

The simulator was modified for on-off control experimentation by the addition of a solenoid-operated air valve behind each thruster nozzle, and short throw, low force, snap switches at each body motion pickoff point. Nozzles of various diameters were provided for each thruster to permit examination of the effect of thrust level. Views of the scooter as it was thus set up are shown in Fig. 7.

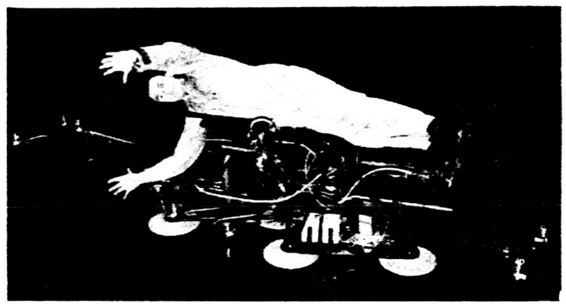


Fig. 7 The Scooter in Its Final Configuration

Initial trials of the on-off system used thrust levels of $10\frac{1}{2}$ pounds for the translational modes, and a torque level of 15 foot-pounds for the pitch mode. Centering springs and detents as in the proportional control experiments were used, and the "off" zones of the controls were made fairly large. The flyability of this arrangement turned out to be much better than expected, but several deficiencies stood out quite clearly. For one, the "off" zones were far too large, giving a subjective impression resembling unduly low gain in the proportional system. Secondly, there was an annoyingly large hysteresis in the switching arrangement, which created the effect of requiring a positive effort to shut off a thruster once it had been turned on. Because of the flyer's neuromuscular time lag this put a noticeable lower limit on the minimum duration of a thrust burst (perhaps $\frac{1}{4}$ second), resulting in constant overcontrolling and "limit-cycle" type of behavior during attempts at delicate maneuvering. And thirdly, 10½ pounds of thrust was much too high, clearly aggravating the hysteresis problem and essentially precluding precision control. This thrust level also caused a peculiar dynamic instability, characterized by a high frequency (2 cps), limit cycle type of oscillation in the waist-bending mode whenever the flyer arched back against the spring just to the edge of switch closure. This phenomenon was not particularly debilitating because it occurred only rarely and could be stopped by simply relaxing, but it does illustrate a potential problem with on-off systems that could very well dictate such factors as thruster location, centering spring sizes, and "off" zone minima.

Following these experiments, the "guilty" parameters were readjusted to the levels shown in Table I. Flight with this configuration turned out to be remarkably good. Delicate maneuvers could be made with precision, and the flying, though done in a style noticeably different from that of the proportional control system, was quite natural.

Table I

NOMINAL PHYSICAL CHARACTERISTICS

	Ankle	Knee	Waist
Off Zone	± 1¼ deg	± 1¼ deg	± 1 deg
Friction	Nil	Nil	Nil
Turn-On Torque	± 16 in.-lb	± 45 in.-lb	± 40 in.-lb
On-Off Differential	4 in.-lb	12 in.-lb	18 in.-lb
Detent Torque	± 8 in.-lb	± 30 in.-lb	Nil
Thruster Effort	± 15 ft-lb	± 2½ lb	± 2½ lb
Mass Scooter & Man	15 Slugs		
Mom. of Inertia Scooter & Man	42 Slug-ft^2		

As in the proportional control experimentation, configurations with and without centering springs behaved quite differently. As before, springs benefitted the novice more than the expert and called for reduction of the dead zones (in this case the "off" zones). But, unlike the proportional case, springs seemed to be preferred by both expert and novice. A strong tendency toward limit-cycle type of operation without springs is the probable explanation.

Although the basic control parameters (thrust, "off" zone size, and control-centering strength) have admittedly not been optimized, on-off control has nevertheless been shown to be practical.

Several subjective impressions regarding the relative behavior of on-off and proportional control systems have evolved:

1) The character of the flying of the two systems is clearly different. The proportional system seems to promote simultaneous operation of the various controls with a consequent feeling of continuity and smoothness during complex maneuvers. On-off controlling, on the other hand, seems to be done primarily sequentially, so that maneuvering becomes a series of discreet operations. (Of course, the actual flight path is smooth and essentially as precise as that of the proportional system.) The feeling of smooth continuity in proportional flying is particularly striking and pleasant immediately after transition from an extended period of practice in on-off control. This may, however, result as much from the character of the jet sounds — which change from a cacaphony of brain stabbing blasts to a modulated hissing — as from actual motion effects.

2) Fast maneuvering is done more confidently with the proportional system. This undoubtedly stems from the availability of larger thrusts that can be used as "safety margins" to compensate for any misjudgments in speed. With the on-off control only one level of "braking" is available and the flyer must therefore be more skillful in his selection of braking points, particularly if he is trying to operate as smoothly as possible. Of course if the maximum proportional thrust were not larger than the on-off value, this conclusion would be invalid, and in fact the proportional flyer might have <u>more</u> trouble with fast maneuvers if "running out of control power" comes as a surprise.

The whole question of the desirability of fast maneuvering is complicated by the fact that velocity is equivalent to fuel increment, and it is therefore desirable from the economy standpoint to keep all motion as slow as possible. On the other hand, factors such as the limits of human patience or the need to get a job done quickly may overbear economy at some point. Thus the parameters that govern fast maneuverability ought eventually to be examined in detail. It is clear, here, that control power is a strong parameter up to a point, but that human factors such as ability to judge and predict, and neuromuscular lags must enter the picture sooner or later.

On balance, proportional control appears to be generally better than on-off control, but not so much better that some engineering consideration such as simplicity of thruster actuation might not specify the use of an on-off system.

Yaw Control and the Current Design Thinking

For some time the Grumman idea has been that body-twist is the appropriate natural motion for controlling yaw. It could not be proved, however, until the recent completion of the yaw control simulator (Fig. 3). To use this device the pilot stands on the platform and is strapped to the "T" bar. Body-twist, which commands motor output torque, is measured as the angular displacement between the platform and the bar, and the motor drives either the pilot's feet (via the platform), or his body (via the metal bar).

Two important results were dramatically demonstrated during preliminary experiments with this simulator. First, yaw control is just as natural as pitch and roll control. In fact, the pilots who have "flown" the simulator have not required any learning. The other important result is that driving the feet provides the pilot with more natural force feedback than driving the body, and thereby results in a much more instinctive and precise control. This result led to a brief reevaluation of pitch control on the scooter, with pitching torques applied to the feet. Here again, applying torques to the feet was found to be superior. The results of these preliminary experiments indicate that a free floating spaceman's control mechanism should apply forces and torques directly to the feet and legs.

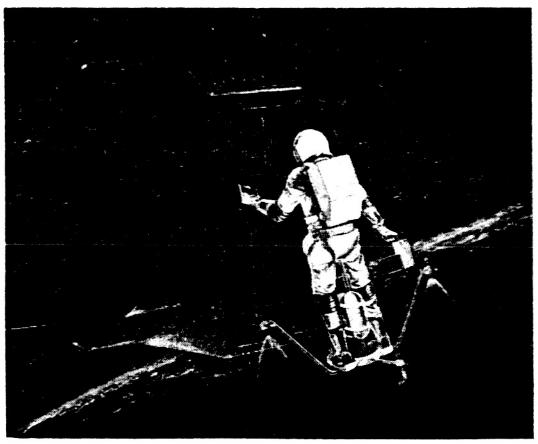


Fig. 8 Design for EVA Control System

This philosophy has been applied to the preliminary design of a prototype flight system. An artist's conception of the system as it is currently envisioned is shown in Fig. 8. It provides the five separate modes of control that have been discussed (pitch, roll, yaw, and fore-and-aft and up-and-down translations). The rationale for excluding lateral translation is, basically, that lateral translation would be needed only for close-in work and in small amounts, and therefore could be adequately effected by use of a "backing and filling" technique involving yaw and fore-and-aft control. This idea is admittedly a speculation that would have to be demonstrated, but in any case lateral translation <u>could</u> be added to the design at a certain cost in complexity.

An interesting feature of the design shown is that all thruster valving functions are carried out in the compact mechanism between the feet, and that, essentially, the feet become the agents for all control. This arrangement, besides being appealingly simple, eliminates some of the control harmony problems that ensue from picking off body deflections higher up.

QUESTIONS AND SPECULATIONS

The experimentation carried out to date has proved a basic concept, but there remains a number of possibly crucial, unanswered questions. Some speculative discussion of these follows.

Are More Than Three Degrees of Control Freedom Practical?

This is the crucial question, and it is not likely to be answered with any finality until a complete system can be tried, either in flight or in a complete-motion simulator. There are some encouraging signs, however. For instance, there is the clearly demonstrated naturalness of pitch, roll and yaw control alone in one-g and "zero-g," and there is Zimmerman's demonstration that pitch and roll can be combined without upsetting their instinctive operation. These lead easily to the speculation that control of all rotations simultaneously can be just as natural and instinctive as control of one alone. If this can indeed be shown, there is room for a good deal of optimism that control of at least five degrees of freedom will be little, if any, harder than the presently demonstrated three. Thus it seems that the crucial experiment for the near future must demonstrate the simultaneous use of the three rotational control modes.

Are All Six Degrees of Control Freedom Necessary?

This question can be asked in connection with ideas not only of human capacity, but of mechanical complexity. Under the assumption that complete control of rotation is vital to the performance of space tasks and is relatively easy to accomplish, the question becomes, "Are three degrees of translational control freedom necessary?" At one point during the experimentation described in this report, the question was phrased, "Could, for instance, control of vertical translation be successfully eliminated?" The answer turned out (not too unexpectedly) to be an unqualified "No;" the mechanical process of "backing and filling," or "tacking," (using pitch rotation), to effect a change in vertical position proved to be unacceptably clumsy. But it might be speculated that the same process using yaw rotation to effect a lateral translation might not be at all clumsy, because yawing (as in body twisting) is quick and easy, and requires little space. This philosophy has, in fact, dominated the preliminary design thinking to date. Definite proof of the concept must be obtained, however, before any serious, detailed designing of a prototype system can proceed.

Does a Space Suit Interfere?

One of the principal artifacts of space suit technology today is stiffness. Therefore, any activity of a spaceman that requires extensive flexing of his body must be looked at askance, and it is only natural that doubt should arise in this respect concerning a control system that requires flexing of the hips, knees, and ankles. The present experimentation has shown, however, that the gains preferred in this system are so high that there is very little visible flexing of the body, even during spirited maneuvering. The speculation here, therefore, is that the foot and leg control concept, far from being incompatible with space suit operation, is in fact particularly appropriate to it.

What About System Safety?

Two kinds of unwelcome system failures are conceivable: one in which the system dies, leaving the spaceman stranded, and one in which the system goes berserk. Of course, the latter would usually lead to the former.

For the stranding situation, one can think in terms of a simple, emergency backup system (such as the present "space gun"), or in terms of retrieval of the stranded spaceman by his buddy in the mother vehicle. A certain amount of training in the use of a space gun could be required, however, since the spaceman might well be left with a rotation to be gotten rid of before he could attempt to return to his vehicle.

For the berserk-system case one thinks primarily of automatic and manual system cutoffs. A rotation cutoff would most likely have to be automatic, because very nasty spin rates can be built up in fairly short times. It should be possible to devise some sort of rotation sensing mechanism, perhaps based on centrifugal or Coriolis effects, which would respond to the emergency but not to ordinary operations. Translation cutoff could probably be done manually.

SUMMARY OF MAJOR CONCLUSIONS

1. The basic concept of precise, hands-free control of spaceman maneuvering by exploitation of instinctive muscular responses of the feet and legs is practical.

2. Accurate, natural control of gravity-free motion in a plane has been demonstrated.

3. A control system should include separate and uncoupled control of the individual degrees of freedom, but control of all six may not be necessary.

4. Ankle deflection for pitch control, differential foot lifting for roll control hip twisting for yaw control, squatting for vertical control, and waist bending for fore-and-aft control are instinctive responses.

5. Control mode gains (acceleration per unit of body deflection) should be high, resulting in little or no body flexure noticeable to an observer.

6. Both proportional and on-off control are practical. Proportional control is slightly preferable to the flyer.

7. The most natural, instinctive, and precise control is achieved when control forces and torques are applied as feedback to the appropriate "controllers" (e.g., pitching torque applied to feet). If control forces are not applied as feedback, mild centering devices on the control pickoffs are generally desirable.

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